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Investigation of Unsteady Airloads on Wings with Oscillating Control for Active Control Purposes

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

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AGARD Report No.699

INVESTIGATION OF UNSTEADY AIRLOADS ON WINGS WITH OSCILLATING CONTROL FOR ACTIVE CONTROL PURPOSES

by

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Paper presented at the 52nd Meeting of the AGARD Structures and Materials Panel
held in Çeşme, Turkey on 5–10 April 1981.

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PREFACE

Knowledge of the unsteady aerodynamic loading on oscillating wings with control surfaces is of special concern in aeroelastic investigations to determine power requirements for active control system applications. In view of the long recognized inadequacy of linearized methods for an analytical prediction of these unsteady airloads, the introduction of such effects as finite thickness, steady mean angle of attack and slot geometry into the theory promise to yield more realistic results.

The present paper, presented as a Pilot Paper in the Session of the Sub-Committee of Aeroelasticity at the 52nd Meeting of the Structures and Materials Panel at Çeşme (Izmir) in Spring, 1981, is an interesting first step toward this aim.

H.FÖRSCHING
Member, Sub-Comminttee on
Aeroelasticity

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Summary

Intensive experimental investigations have been carried out on a wing section with oscillating control including a streamlined gap between both wing parts. Steady as well as unsteady pressure distributions have been measured outside and inside the gap region for various incidences, flap angles and frequencies.

In addition to the experimental investigations, a calculation procedure has been developed taking into account the real boundaries of the configuration including the gap region and assuming the fixed wing part and the oscillating control as two lifting systems with two Kutta conditions and correspondingly two wakes behind wing and control.

Comparisons between theory and experiment are discussed in detail and the major influences and effects of viscosity are pointed out. The results lead to special conclusions for the applicability of lifting systems for active control purposes.

1. Introduction

For the application of active control technologies with respect to gust alleviation, flutter suppression, etc., the detailed knowledge of the steady as well as unsteady airloads on wings with fast-moving controls is of major importance for a successful design. However, there still exists a variety of problems related to profile geometry, gap flow, steady mean flap deflection, three-dimensional effects and in particular viscous and transonic effects, all of which have considerable influence on the unsteady airloads of wing/control configurations. Most of these problems can only be solved approximately by the lifting surface theory. But it is also possible to develop a more direct prediction method based on potential theory, where surface singularity distributions are used and where the exact geometrical boundary condition is taken into account. If results of such a complete potential theory are compared with experimental data, effects of viscosity and flow regions where these effects are dominant can be identified.

In Refs.[1], [2], experimental results are given for a wing with oscillating control including a streamlined gap in low subsonic flow. In Ref.[3], a prediction method is described to calculate steady and unsteady airloads on lifting bodies including the exact boundary condition on the wing surface and taking into account the exact Bernoulli equation in a body-fixed frame of reference. This prediction method has been modified for the present problem by representing two lifting bodies which are separated only by a small streamlined gap. Measured and calculated pressure distributions have been compared for a variety of parameters, such as incidence, steady mean flap deflection, aspect ratio and oscillation frequency [4]. The following discussion will concentrate on some selected results where the effects of viscosity are severe. Steady boundary layer calculations and frequency analyses of the measured fluctuating pressures are helpful in identifying the particular viscous phenomena involved, e.g. transition, laminar/turbulent separation. Special correction procedures are then applied to consider the main effects of viscosity on the unsteady airloads.

2. Analytical method

The prediction method used for the present investigations is a surface singularity method, i.e. the real body surface is represented by a continuous distribution of sources and doublets where the latter are extended from the wing trailing edge into the free flow forming a steady (and unsteady) wake surface. In the present case two lifting bodies are divided by only a small gap such that strong aerodynamic interference effects occur. In Fig.1 the geometrical details within the gap region are shown for the three investigated flap deflections: $\delta = 0°/10°/20°$. The basic airfoil is a NACA 0010 section with corresponding modifications of the gap. To simulate the flow in a proper manner, two wake surfaces emanating from both wing and control trailing edges and two Kutta conditions are taken into account. The wakes are assumed to leave the trailing edges at an angle of $\alpha/2$ (α = section incidence). This wake incidence has been found to be adequate although a change of the wake incidence between zero and α has shown no considerable influences on the steady or on the unsteady airloads, [4].

Fig.1 illustrates that, due to the special geometrical arrangement where points on the control are located very close to the wake surface of the wing, careful evaluation of the aerodynamic influence functions of the wake is necessary. In Ref.[4] the behavior of the velocity potential and induced velocities of a wake strip in the vicinity of or directly on the inducing surface is outlined in detail. As a result of this investigation it has been found [4] that the velocity potential jumps by 4π if the control point moves through the wake surface from the upper to the lower side or vice versa. The induced velocities of a wake surface however remain continuous if the control point moves through the surface and has a maximum value on the wake surface itself.

Fig.1 shows also the panel arrangement and control point locations in the gap region with a total of 60 panels on the wing and 40 panels on the control for each individual section. For the three-dimensional method applied to the present problem the wing is subdivided further into three strips in spanwise direction with a total of 300 control points. Only one-half of the wing is represented by control points. The second symmetric half is taken into account by applying the usual symmetry conditions.

3. Experiment

The experimental investigations have been performed in cooperation with MBB/Hamburg in the low-speed 3m x 3m wind tunnel of the DFVLR in Goettingen, [1]. The model with 1m chord and 1.5 span was mounted between endplates. The midsection was equipped with a total of 45 pressure orifices which were connected to a pressure transducer by a tube/scanning valve system. In addition, 10 in situ pressure transducers were installed within the same section. The parameters varied during the test were:

1) Section incidence $0° \le \alpha \le 12°$,
2) Steady control deflection $0° \le \delta \le 20°$,
3) Oscillation frequency of the control $4\ \mathrm{Hz} \le f \le 15\ \mathrm{Hz}$,
4) Wind speed $20\ \mathrm{m/s} \le U_\infty \le 50\ \mathrm{m/s}$,
5) Open/closed gap between wing and control.

Further details of the test program are given in Ref.[1].

4. Results

In the following sequence of figures only a selection of results obtained by the prediction method and compared with the experimental data can be given. More details are discussed in Ref.[4].

The discussion will concentrate on three different cases:

1) Small incidence, no steady flap deflection:
Figs.2-5 with $\alpha = -1.6°$ and $\delta = 0°$,
2) Moderate incidence and high steady flap deflection:
Figs.6-8 with $\alpha = 6.4°$ and $\delta = 20°$,
3) Moderate incidence and high steady flap deflection with a closed gap:
Figs.9-11 with $\alpha = 6.4°$ and $\delta = 20°$.

In all three cases the oscillation frequency was 8 Hz with a reduced frequency of $\omega^* = 1.006$ with respect to the wing chord.

4.1 Influence of aspect ratio, section incidence and steady flap deflection

With the three-dimensional calculation procedure used for the present calculation it is possible to vary the aspect ratio of the rectangular wing/control configuration. In the experiment the model dismensions were 1m chord and 1.5m span. The aspect ratio was increased by placing the model between endplates. Comparisons between theory and experiment have shown that the real aspect ratio in the experiment was slightly smaller than 3 . Figs.2-5 show the effects of the two different aspect ratios $\Lambda = 3$ and 8 on the steady as well as on the unsteady airloads. There are remarkably large influences of this parameter especially on the real and imaginary pressure distributions of the wing. For further investigations of viscous effects it is important to consider the correct aspect ratio in the analytical method. The aspect ratio $\Lambda = 3$ was therefore taken as the reference value for the further discussions. Figs.2 and 6 show the steady chordwise pressure distributions for small and large incidence/steady flap deflection.

A large pressure maximum is calculated on the wing lower surface within the gap at zero incidence, followed by a similar peak on the control upper surface (Fig.2). These pressure peaks are not represented by the experimental data. With moderate incidence and large flap deflection (Fig.6) the steady pressure distributions exhibit a quite different behavior: the positive pressure peak in the gap region of the wing pressure side is reduced considerably. On the control a strong negative pressure peak is formed on the upper surface. There is obviously better correspondence between theory and experiment in this case. Similar effects due to section incidence and steady flap deflection can be observed for the unsteady pressures on the wing (Figs.3 and 7) and on the control (Figs.4 and 8). In regions where the steady pressures show large deviations compared to experiment, the unsteady pressures do not match the experimental data either. This behavior is obvious in the gap region of the wing lower surface (Figs.3 and 7) and in the gap region of the control upper surface (Fig.4) for $\delta = 0°$, whereas the correspondence between theory and experiment is better in the high flap deflection case (Fig.8).

In all cases investigated, the differences between potential theory and experiment are large within the gap region but these differences can only be observed for the steady as well as for the real parts of the unsteady pressures. It is interesting to point out that the calculated imaginary parts show only small deviations compared to the experimental data.

This observation can be made for the low as well as the high incidence and flap deflection cases.

Fig.5 shows the local lift distributions on wing and control for the low incidence case. The results obtained from lifting surface theory are also included. Large differences between the theory including complete boundary conditions and lifting surface theory can be observed again in the gap region, with a finite pressure peak for $\Delta c_p'$ of the former and with singular behavior (no gap included) for the latter. The experimental data of $\Delta c_p'$ do not correspond well with the theoretical results within the gap regions. The imaginary parts however are in much better agreement.

4.2 Closed gap

The theoretical and experimental results discussed so far were obtained with an open gap. Further measurements have been performed with a closed gap. This position has been achieved simply by placing flexible tape over the gap on the upper surface of the configuration whereas the lower surface remained unchanged. This simple modification of course prevented any flow through the gap, while having the disadvantage that the upper surface was not smooth but had a discontinuity in slope.

In Figs.2-4 (zero flap deflection) and in Figs.6-8 (20° flap deflection) the experimental data for a closed gap have been included. In the zero flap deflection case the differences in the experimental data between the open and closed gap are small. In the high flap deflection case however large deviations occur on the wing upper surface. These effects are obviously influenced by flow separation on the control upper surface.

Figs.9 and 10 show theoretical results for a modified geometry of the wing/control configuration without gap. Upper and lower surfaces have now been approximated by a smooth curve closing the gap. The differences between theoretical results and measured data are severe on the wing upper surface. The measured steady pressures remain approximately constant within the separated region (Fig.9). The real-part pressure distribution exhibits contrary behavior compared to potential theory and the imaginary parts are highly influenced on the control upper surface as well (Fig.10).

4.3 Viscous effects

Assuming that numerical errors of the analytical method and uncertainties in the experimental data are small, the differences between calculated and measured pressures must be attributed to viscosity.

Three different regions and types of viscous effects can be identified for the present wing/control configuration:

1) Turbulent separation at the wing trailing edge within the gap.

2) Turbulent separation on the control upper surface for the case of a closed gap at moderate incidence and high flap deflection.

3) Effects of transition from laminar to turbulent boundary layers, laminar separation bubble.

To investigate these effects in more detail, steady boundary layer calculations [5] have been performed by taking into account the calculated steady pressure distributions. The boundary layer calculations start at the front stagnation point with a laminar boundary layer. The calculation continues until laminar separation is signaled. At the laminar separation point the boundary layer calculation continues with a turbulent boundary layer until turbulent separation occurs where the calculation is then stopped. The point of laminar separation is identified as the transition point.

In the low incidence/flap deflection case (Fig.2) the boundary layer calculation signals a turbulent separation within the gap region on the wing lower side. The flow cannot follow the predicted high pressure rise at this position and separates. Measurement of the fluctuating pressures at the measuring points outside and inside this separated region and the corresponding frequency analyses clearly show the increased level of pressure amplitudes. A similar behavior is observed on the control surface within the gap. It is interesting to notice that high flow-induced pressure amplitudes occur in the very low frequency region less than 5 Hz . Resonance within the gap probably causes these effects.

Fig.2 shows furthermore that the steady pressures on the wing and control within the gap are nearly equal. The calculated separation pressure is slightly higher than the measured data. Correspondingly large are the effects of separation on the real parts of the unsteady pressures on the wing (Fig.3) and control (Fig.4) within the gap. In particular the predicted strong negative pressure peak c_p' on the control is not approached by the real flow.

In the case of high incidence/flap deflection (Fig.6) a turbulent separation of the boundary layer is again signaled on the wing lower surface. The high negative pressure peak on the control upper surface however now accelerates the flow through the gap along the control surface. The viscous effects are not so obvious in this case: they are expressed by a reduction of the flow acceleration along the control with a corresponding reduction of the negative pressure peak c_p' (Fig.8).

Due to the additional impulse from the gap flow, the boundary layer on the control upper surface remains attached even for higher incidences (α = 10.4°, δ = 20°) as long as the gap is open. But if the gap is closed a turbulent separation occurs. The discontinuity in slope provokes separation in the real flow at or close behind the gap. The calculated separation point (Fig.9) however is shifted further downstream due to a continuous slope representing the former gap region.

It has already been mentioned in Ref.[6] that boundary layer transition has a remarkable influence on the unsteady airloads. Transition is assumed to occur at the laminar separation points. At this point a more or less developed laminar separation bubble may occur which is unaccounted for in the boundary layer calculation but which has increasing influence on the unsteady airloads. However these influences are limited to a small region of the profile surfaces. Due to the relatively small number of measuring points in the experiment, effects of transition (laminar separation bubble) are sometimes missed. Conversely these effects may be strong if an orifice happens to be located in the transition region. The predicted results of the real-part pressure distributions include the calculated transition points. Especially in Fig.10 (gap closed) the effects of transition are severe with respect to c_p'. The measured transition points are shifted slightly further downstream compared to their calculated positions.

4.4 Viscous correction procedures

In the foregoing discussion it has been stated that adequate correspondence exists between a complete potential theory and the corresponding experimental data. But this correspondence is reduced considerably if viscous effects are severe. Problems occur for the gap region at low incidence and flap deflection and on the control upper surface for high incidence/flap deflection and a closed gap. Due to the knowledge of the viscous phenomena involved, special correction procedures can be developed to consider the viscous effects by modifying the potential theoretical code.

a) Separation in the gap region.

Fig.2 shows that the steady pressure within the gap is approximately constant. Due to this observation an unsteady pressure can be calculated at the turbulent separation point and extended constantly into the separated region based on a quasi-steady procedure: the steady pressures at the separation point are calculated for $\delta = 0°$ and $\delta = 1°$. From these results a quasi-steady separation pressure can be determined by

$$(1) \qquad (c_p')_{sep} = \frac{(c_p)_{sep(\delta=1°)} - (c_p)_{sep(\delta=0°)}}{1° \cdot \pi/180°}$$

This pressure has been included in Fig.3 (wing) and Fig.4 (control). In both cases it is assumed that $(c_p')_{sep}$ remains constant within the gap. Of great influence are the effects on the control upper surface in reducing the negative pressure peak at this position. The influences of the correction on the local lift distributions (Fig.5) give the correct tendencies and magnitudes: there is a pressure rise of $\Delta c_p'$ at the wing trailing edge (similar to lifting surface theory) but with a final value at the wing trailing edge and a strong reduction of the $\Delta c_p'$ pressure peak on the control.

A corresponding correction for the high incidence/flap deflection cases has not been tried because the assumption of constant pressure through the gap is obviously no longer valid. Again separation occurs on the wing lower surface. Now viscous effects reduce the magnitude of flow acceleration through the gap and therefore reduce the strong pressure peaks on the control upper and lower surfaces. A modelling of these effects necessitates further detailed investigation of the corresponding viscous gap flow.

b) Separation on the control upper surface (gap closed).

Fig.10 shows the real and imaginary pressure distributions for a closed gap and severe differences between potential theory and experiment especially on the control upper surface. In Fig.11 the pressure amplitudes and phase angles are given within this region. The characteristic singularity of $\bar{c}_p$ obtained with the prediction method cannot be found in experiment. The predicted phase angle which starts with zero at the singular point and increases continuously downstream, starts in the experiment with a maximum and then decreases. These contrary behaviors must be attributed to the separation occuring in experiment in the vicinity of the (closed) gap - discontinuity in surface slope - as has been outlined previously. Applying the same quasi-steady procedure described in the previous section, a pressure amplitude can be determined at the turbulent separation point. This amplitude is included in Fig.11. To obtain comparable situations, the amplitude has been extrapolated upstream to the point where separation occured in experiment. From the phase curves in Fig.11 a jump in phase angle of approximately 120° can be observed.

A correction based on the two assumptions of constant pressure amplitude inside the separated region together with a constant phase shift of the unsteady pressures can now be applied and the effects of this correction on the real and imaginary pressure distributions (Fig.10) can be studied: the tendencies and magnitudes for the real-part pressures are quite well represented by the correction. The corrected imaginary parts show the same level as in the experimental case and the same tendencies close to the separation point. Further downstream the corrected imaginary parts deviate from the measured data. This latter effect is due to the simple assumption of the constant jump in phase which is only valid immediately behind the separation point.

The results obtained by the relatively simple correction procedure considering effects of a separated region can of course only indicate main tendencies for unsteady airloads. But the assumption of a constant steady pressure as well as a constant unsteady pressure amplitude within the separated region together with a constant phase shift obviously includes the main effects.

Analyzing the fluctuating pressures within the separated region from corresponding power spectra, it becomes clear that several additional effects play an important role for unsteady airloads: pressure amplitudes are not only determined by the oscillatory movement of the control (motion-induced unsteady airloads) but also by flow-induced components. Further detailed investigations are necessary to gain some insight into the mechanism by which these motion-induced and flow-induced components act together. Of further interest are the phase relationships between measured and calculated data. It makes sense to assume that the separation point and with it the whole free separation region on the oscillating control surface moves with a special phase shift compared to the non-separated flow. But a constant phase shift can of course be only a rough approximation. The power spectra of the unsteady pressures show increasingly higher harmonics within the separated region demonstrating that these relationships are no longer simply sinusoidal.

5. Conclusion

Steady and unsteady pressure distributions have been investigated theoretically and experimentally on a wing/control configuration including a streamlined gap. Taking into account the exact geometrical boundary condition of the configuration and applying the exact Bernoulli equation, the predicted results and the experimental data indicate by comparison the points at which viscous effects are severe.

Particularly in the low incidence and flap deflection cases separation effects are observed within the gap. These effects influence mainly the real part pressure distributions on the wing and control. The strong pressure peaks on the control are reduced considerably by these effects.

If the gap is closed, separation occurs on the control upper surface for moderate incidence and large flap deflection angles. The real and imaginary pressures within this separated region show the expected contrary behavior compared to potential theory.

Based on the assumption that the pressure amplitude within the separation region remains approximately constant together with a constant phase shift within the free separation region on the control upper surface, correction procedures are able to describe the main features of the real and imaginary pressure distributions within the separated flow regime. The pressure amplitude can be calculated on a quasi-steady basis from a boundary layer calculation determining the steady pressures within the turbulent separation points.

Further intensive investigations must be concentrated on the detailed investigation of the flow-induced fluctuating pressures within a separated region and the interaction between flow-induced and motion-induced pressures and airloads. Viscous effects, in particular separation, have of course strong influences on the effectiveness of active control systems. The maximum limit of unsteady airloads and hinge moments on a control are given by potential theory (including a smooth flow off the trailing edges). In a real flow the airloads may be reduced considerably by viscous effects. To achieve effective designs for active control systems as far as aerodynamic influences are concerned, one should therefore concentrate on the prevention or at least reduction of the various forms of viscous phenomena.

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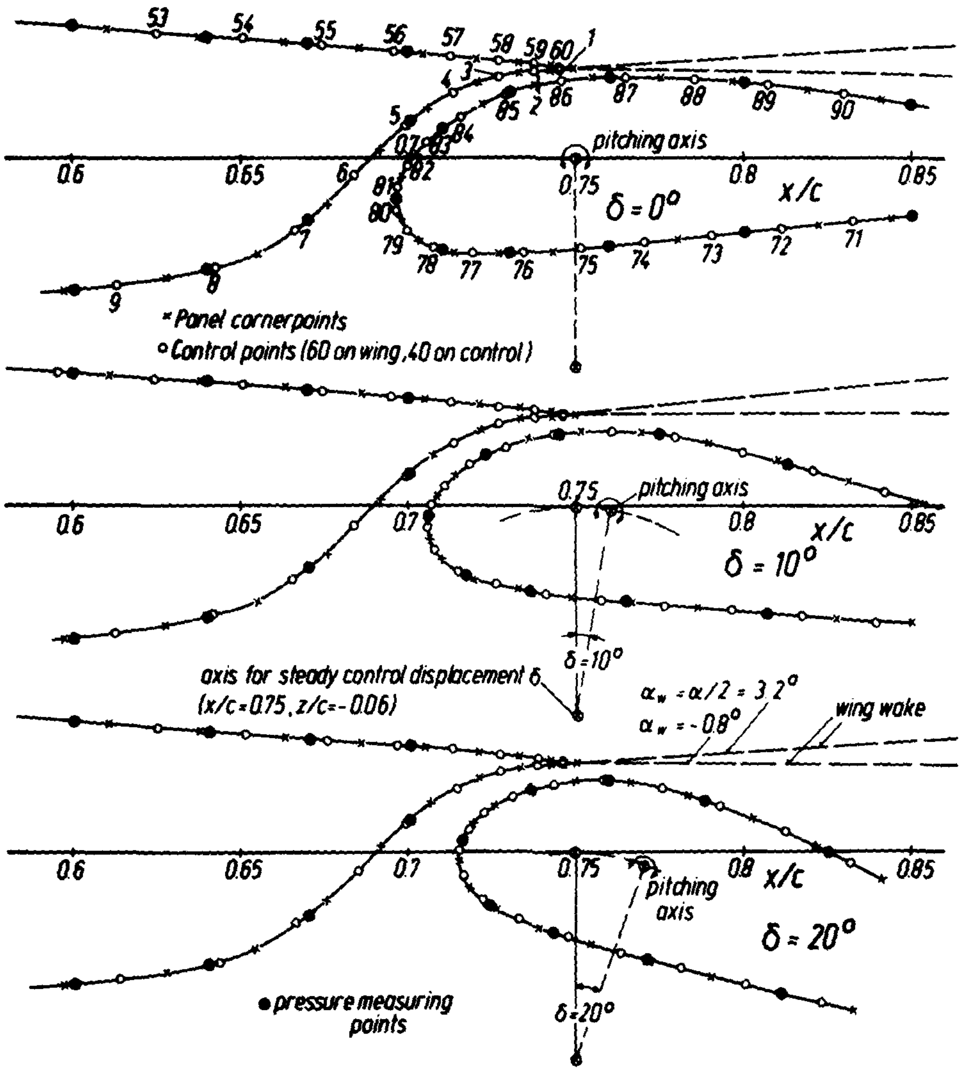


Fig. 1: Details of flap geometry for steady mean flap deflections: δ = 0°/10°/20°.

Locations of measuring points.

Locations of panel corner points and control points for prediction method.

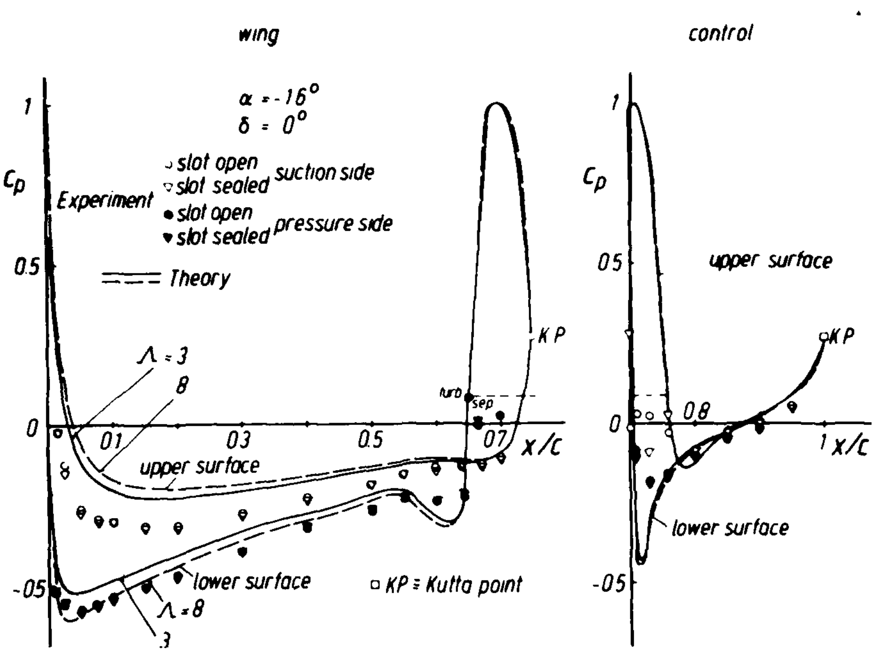


Fig.2: Steady chordwise pressure distributions on wing and control for low steady mean incidence and zero mean flap deflection, α = -1.6°, δ = 0°.

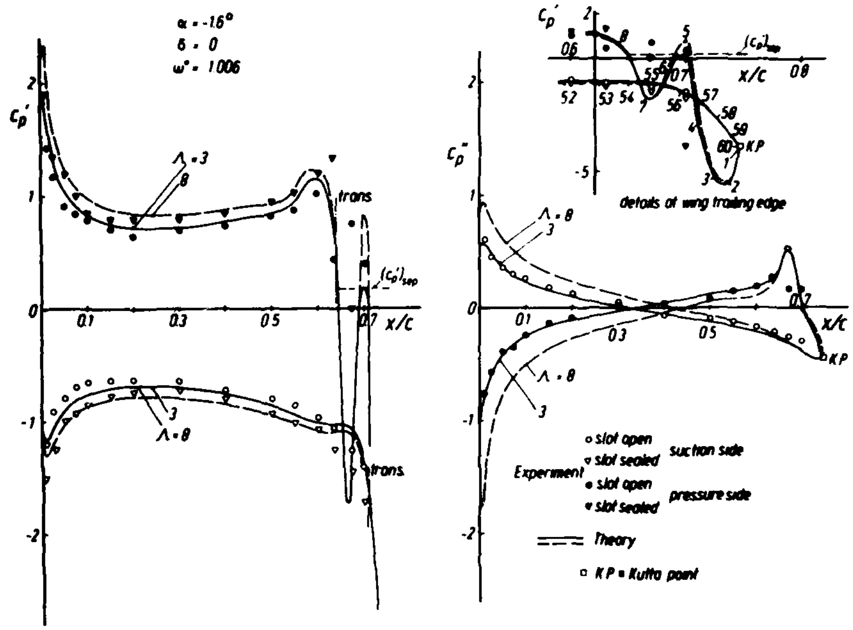


Fig.3: Unsteady chordwise pressure distributions on the wing.

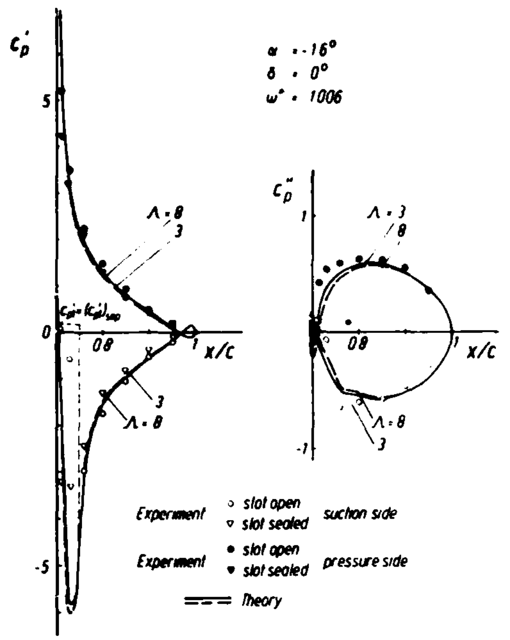


Fig.4: Unsteady chordwise pressure distributions on the control for low steady mean incidence and zero mean flap deflection, α = -1.6°, δ = 0°.

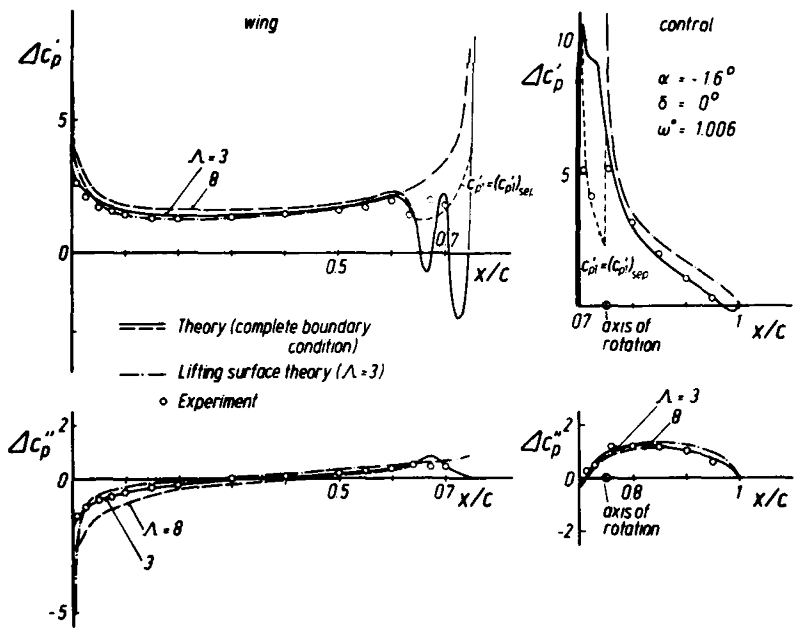
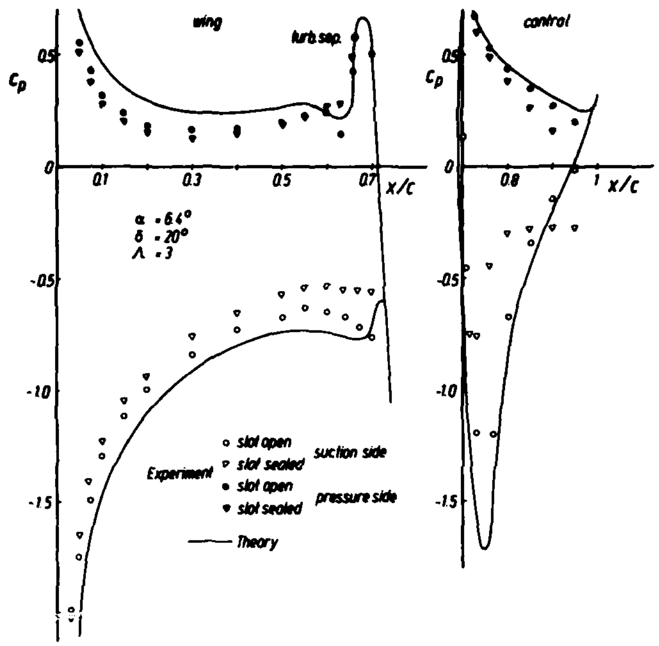
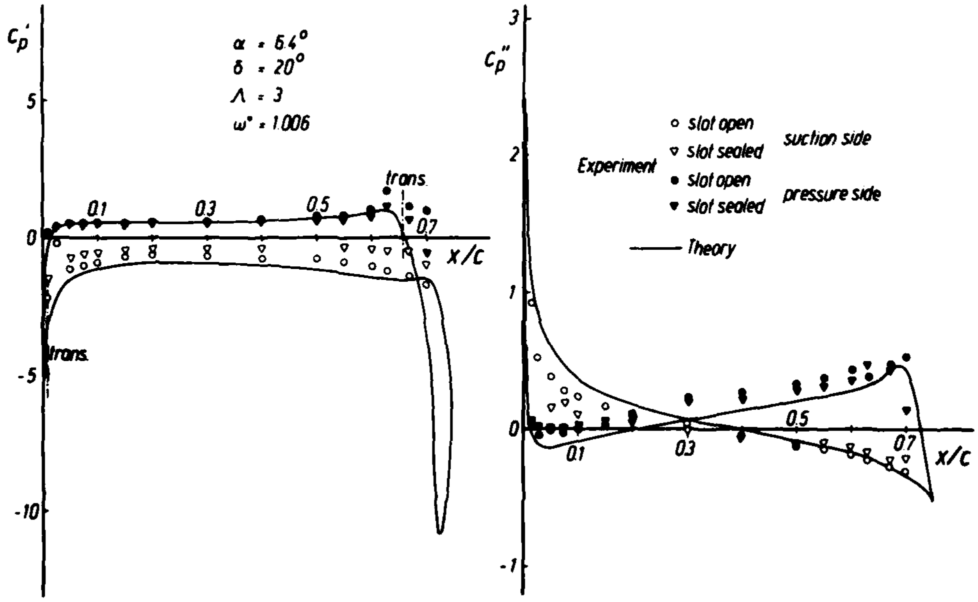


Fig.5: Local lift distributions on wing and control. Comparisons between complete potential theory, lifting surface theory and experiment.



<u>Fig.6</u>: Steady chordwise pressure distributions on wing and control for moderate steady mean incidence and high steady flap deflection, α = 6.4°, δ = 20°



<u>Fig.7</u>: Unsteady chordwise pressure distributions on the wing.

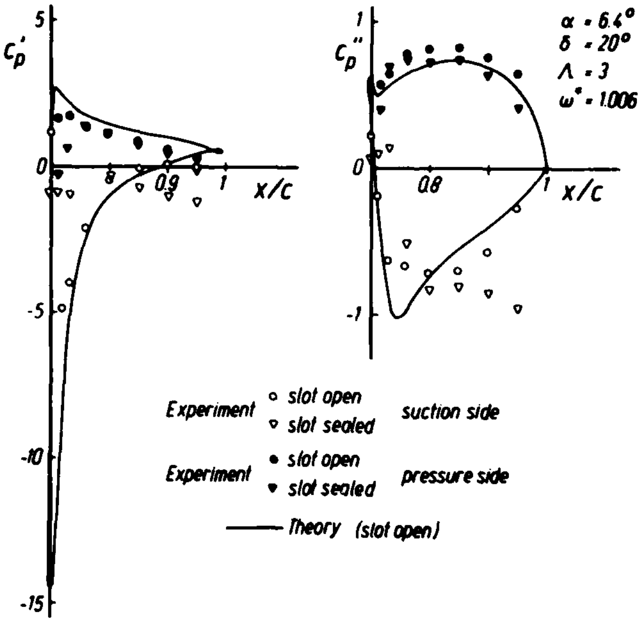


Fig.8: Unsteady chordwise pressure distributions on the control for moderate steady mean incidence and high steady flap deflection, α = 6.4°, δ = 20°.

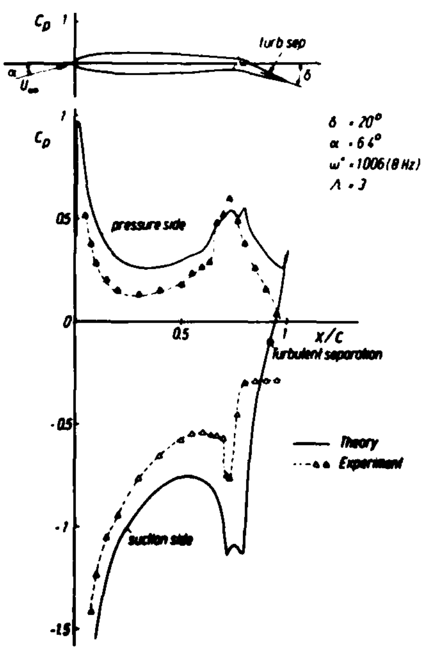


Fig.9: Steady chordwise pressure distributions, slot closed. In the experiment the gap was closed by flexible tape fixed on the wing upper surface. For the prediction method the gap region was replaced by smooth surfaces, α = 6.4° , δ = 20°.

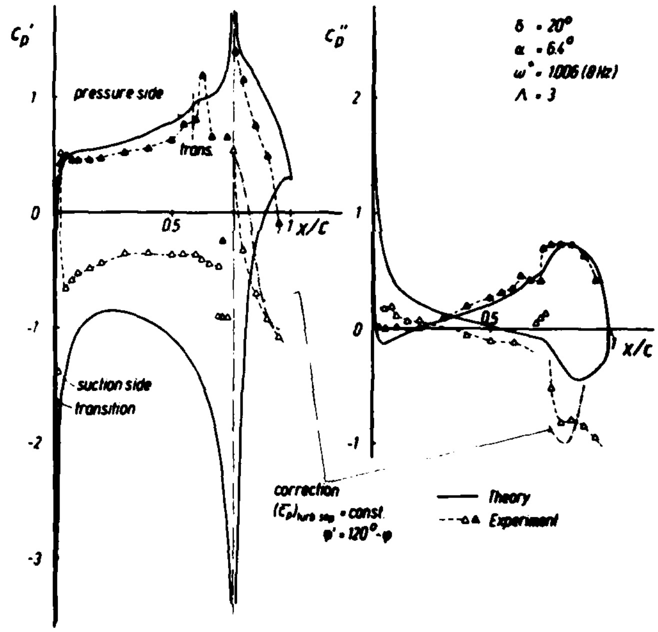


Fig.10: Unsteady chordwise pressure distributions, slot closed. Correction of the calculated unsteady airloads inside the separated region on the control upper surface.

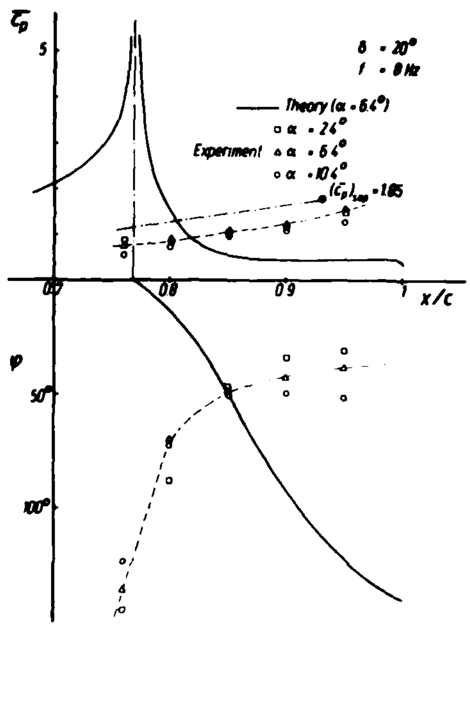


Fig.11: Measured and calculated amplitudes and phase angles on control upper surface.

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Oscillations	Active control

14. Abstract

Intensive experimental investigations have been carried out on a wing section with oscillating control including a streamlined gap between both wing parts. Steady as well as unsteady pressure distributions have been measured outside and inside the gap region for various incidences, flap angles and frequencies.

In addition to the experimental investigations, a calculation procedure has been developed taking into account the real boundaries of the configuration including the gap region and assuming the fixed wing part and the oscillating control as two lifting systems with two Kutta conditions and correspondingly two wakes behind wing and control.

Comparisons between theory and experiment are discussed in detail and the major influences and effects of viscosity are pointed out. The results lead to special conclusions for the applicability of lifting systems for active control purposes.

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Aerodynamic loads
Unsteady flow
Oscillations
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